APPENDIX D:

WIND ENERGY TECHNOLOGY OVERVIEW

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Modern wind energy technologies rely heavily on the very complex scientific discipline of fluid dynamics (which includes the study of the atmosphere) and the equally complex engineering discipline of aerodynamics. A comprehensive treatment of either of these disciplines is well beyond the scope of this programmatic environmental impact statement (PEIS). The discussions that follow are intended only to establish a basic understanding of wind technology and the factors that control its evolution. References are provided for those who wish to have a more detailed understanding of wind technology.

This appendix provides an overview of the fundamentals of wind energy and wind energy technologies, describes the major components of modern wind turbines, and introduces terms that are unique to the field of electric power generation using wind energy. Important site characteristics and critical engineering aspects of wind energy technologies are presented, and their respective influences on future development decisions are discussed.[1] An overview of the current state of wind energy technology and ongoing research and development (R&D) is provided. Descriptions of a typical wind energy project and the major actions associated with each phase of development — site monitoring and testing, construction, operation, and decommissioning — are presented in Chapter 3 of this PEIS.

D.1 IMPORTANT TERMS AND CONVENTIONS

Discussions in the following sections introduce important terms and conventions, some of which are unique to the wind energy industry. The terms and conventions are described in the text where they are first introduced. Additional details are provided in the glossary of this PEIS (Chapter 10).

D.2 WIND ENERGY

Wind represents the kinetic energy of the atmosphere. In simplest terms, wind is the movement of air in the earth's atmosphere relative to a fixed point on the earth's surface. The major initiator of that movement is the uneven heating of the earth's surface by solar radiation. The materials that compose the patchwork of the earth's surface (e.g., vegetation, exposed rock, snow/ice cover, and water) react differently to solar radiation, absorbing heat energy and reflecting some of that energy back into the atmosphere at different rates. The result is a nonequilibrium condition in which adjacent air masses have different heat energies and, as a result of adiabatic expansion or compression, different barometric pressures. Wind is one result

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[1] Wind farm developers and their investment capitalists must select among myriad options related to turbine design and site development and operation. Only those factors that have direct relationships to direct or cumulative impacting factors that are analyzed in this PEIS are discussed here.

of the atmosphere's attempt to normalize those differences and return to the lowest possible equilibrium state. The rotation of the earth around its axis initially causes a generally uniform global flow of air from west to east; however, many other factors add complexity to the dynamics of the earth's atmosphere. The text box on the next page has additional information on atmospheric motion.

D.3 EXTRACTING THE POWER OF THE WIND

The kinetic energy of wind is related to its velocity. This relationship is represented mathematically by the following equation:

$$P = \tfrac{1}{2} \times \rho \times A \times V^3 \,, \tag{D.1}$$

where

P = wind power (W),

ρ = air density (typically 2.70 lb/m^3 [1.225 kg/m^3] at sea level and 59°F [15°C]),

A = cross-sectional area of the wind being measured (m^2), and

V = mean velocity of the wind within the measured cross section (m/s).

A careful examination of this power equation reveals the following important fundamental truths about wind energy. Both the air's density and the cross-sectional area of the wind being intercepted have a direct relationship to wind power. The air's density varies with temperature, elevation, and humidity, but, in all instances, the density remains relatively low. Thus, any changes to air density have a minimal effect on the wind's inherent power. Doubling the cross-sectional area of a wind front leads to a doubling of the intrinsic power. Most important to wind farmers is the fact that the wind's power is proportional to the cube of its average velocity. Thus, a doubling of the average or mean wind speed results in an eightfold increase in its power.

As a practical matter, wind energy technologists focus on the wind's "power density" or power per unit area of wind being intercepted, expressed in W/m^2. Simple manipulation of the above power equation allows power density to be calculated by using the following expression:

$$\text{Power density} = P/A = \tfrac{1}{2} \times \rho \times V^3. \tag{D.2}$$

The height of the wind above the earth's surface also affects the average wind speed. Frictional drag and obstructions near the surface of the earth generally retard wind speed and induce a phenomenon known as wind shear (the change in a wind's speed with elevation). The rate at which wind speed increases with height varies on the basis of local conditions of the topography, terrain, and climate, with the greatest rates of increase observed over the roughest terrain. Unique local conditions notwithstanding, a reliable approximation is that wind speed increases approximately 10% with each doubling of height (Gipe 1995).

Understanding Atmospheric Motion

Wind represents the earth's atmosphere in motion. Understanding the development and progression of wind involves understanding the complex array of forces that constantly act upon the earth's atmosphere and cause its continuous motion. The velocity, direction, and variability of wind are products of those collective forces. The major forces at play include basic laws of thermodynamics, the force of the earth's gravity, frictional forces and obstructions imposed by the topography of the earth's surface, and the Coriolis effect caused by the earth's rotation. Thermodynamics governs the ways in which a given air mass behaves as it exchanges heat energy with its surroundings. Although the atmosphere's density is quite low, the gravitational forces of the earth nevertheless exert a constant downward force on the atmosphere that continuously affects its behavior.

It can be intuitively understood that the surface of the earth over which wind passes can also have some influence on wind, especially in the planetary boundary layer (the portion of the atmosphere immediately above the earth's surface). Topography can either increase or decrease wind speed in localized areas. Topography can also contribute to or induce wind shear (the rapid change of direction of wind with altitude). When other overriding forces are absent, topographic obstructions and friction at the earth's surface generally result in higher wind speeds at higher altitudes, with the highest wind speeds being achieved when all surface influences disappear. This wind is called the geostropic wind. The height or thickness of the planetary boundary layer varies over the surface of the earth (and actually changes slightly over the course of the day as a result of solar heating), reaching to thousands of feet in some locations. For the practical purpose of harvesting wind energy, the wind regime of greatest interest is contained completely within the boundary layer and, ideally, is composed largely of geostrophic wind.

The force commonly referred to as the Coriolis effect is more difficult to comprehend. Although it is easy to understand wind as being the motion of the atmosphere relative to one's point of observation on the surface of the earth, it is also important to recognize that one's point of observation, while it is fixed on the earth's surface, is not fixed in space, and it is itself moving as the result of both the earth's rotation and its orbit around the sun. The Coriolis effect is most easily defined as that apparent force on the wind that would not have otherwise occurred except for the earth's rotation and movement through space. It is manifested as a bending or redirection of the wind into circular patterns as air masses move from high-pressure to low-pressure areas. The magnitude of the Coriolis effect is a function of latitude. Winds directly above the earth's equator and moving in a direction parallel to the earth's axis of rotation experience very little in the way of a Coriolis effect. Winds occurring at other latitudes experience a Coriolis effect that is roughly proportional to the distance of that latitude from the equator. This fact can be easily understood by recognizing that any given point on the earth's surface along its equator is traveling at roughly 373 mph (600 km/h) around the earth's axis of rotation, while both the north and south poles have virtually no angular momentum.

Other characteristics of atmospheric motion that are of great practical significance to wind energy development are those factors that contribute to its variability over both time and geographic location. These factors include topography-induced variations, annual and seasonal wind speed variability, synoptic variations (resulting from or influenced by broad-area weather patterns and storm fronts), diurnal variations (reflecting changes in levels of solar radiation over a 24-hour cycle), turbulence (the uneven, chaotic motion of air), wind gusts, and extreme wind speeds. All such factors are critical to identifying ideal wind regimes and to designing wind turbines that can capture wind energy with the greatest efficiency while still withstanding the forces to which they will be exposed over their lifetimes. Since most of these forces exhibit their greatest influence on atmospheric motion in the planetary boundary layer (the portion of the atmosphere in which wind turbines normally operate), their influence on siting decisions and turbine design is substantial. While many of these variability factors can be intuitively understood, many others cannot. This uncertainty leads directly to the difficulties that now exist in accurately predicting weather. This uncertainty also greatly increases the complexity involved in selecting and developing the ideal wind farm.

Because wind flows not only more quickly but also more uniformly as the elevation from the earth's surface increases, the power contained in the wind is both greater and more easily extractable at higher elevations. Because turbulence decreases as the distance from surface obstructions increases, power actually increases faster with height than the relationship of power to the cube of the wind's speed would indicate. Thus, for example, a fivefold increase in height results in nearly a doubling of available wind power. To take advantage of this relationship, wind turbine developers pursue designs that not only allow the capture of the greatest cross-sectional area of wind but also allow the capture of wind at the highest practical elevation possible. There are trade-offs, however. Higher turbine elevations require more substantial support systems (both towers and their foundations) and substantially greater initial investments. Higher altitudes also subject the rotor and the nacelle, as well as the tower itself, to greater aerodynamic forces, which can require extensive design modifications and can shorten the expected operating lives of the tower and its components. Finally, operation and maintenance (O&M) activities can also be more complicated and costly with increases in the elevation of the rotor.

D.3.1 Characterizing Candidate Sites and Site Selection

The wind energy industry has adopted a convention by which annual average wind power densities and speeds are divided into seven power classes. It is also common practice to represent wind speed at a specified elevation above the land surface to allow comparative evaluations of sites within a given class to be made. To facilitate the identification of ideal wind regimes, the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) has developed comprehensive wind maps for the United States that show the spatial distributions of these power classes. These maps were derived from meteorological data collected at thousands of locations. Figure D-1 shows the wind resource distribution map for the contiguous 48 states. (Power density maps have also been developed for Alaska and Hawaii. However, since lands administered by the Bureau of Land Management [BLM] in those states are outside the scope of this PEIS, maps for those two states are not displayed here.) A more detailed discussion on the distribution of ideal wind regimes and more detailed maps showing ideal wind regimes on BLM-administered lands and their locations relative to existing electric power transmission lines are provided in Appendix B. Developers using currently available wind turbine technologies have found that sites with wind power densities at Class 4 or higher represent economically viable sites for a wind farm.

These wind maps serve only as a preliminary screening tool for site selection. Developers must still investigate the properties of the wind regime at any candidate site in much greater detail before assigning a practical value to the site and deciding on a course of development. The principal limitation to the wind power distribution map displayed here is that it shows only the annualized average wind speeds and power densities. Two sites with identical annual average wind speeds and power densities may have arrived at those average values by entirely different paths. Sites whose average speeds and power densities are the product of widely varying instantaneous wind speeds over time are much less attractive than sites displaying lesser wind speed variations over time with few or no instances of excessive, potentially damaging wind speeds.

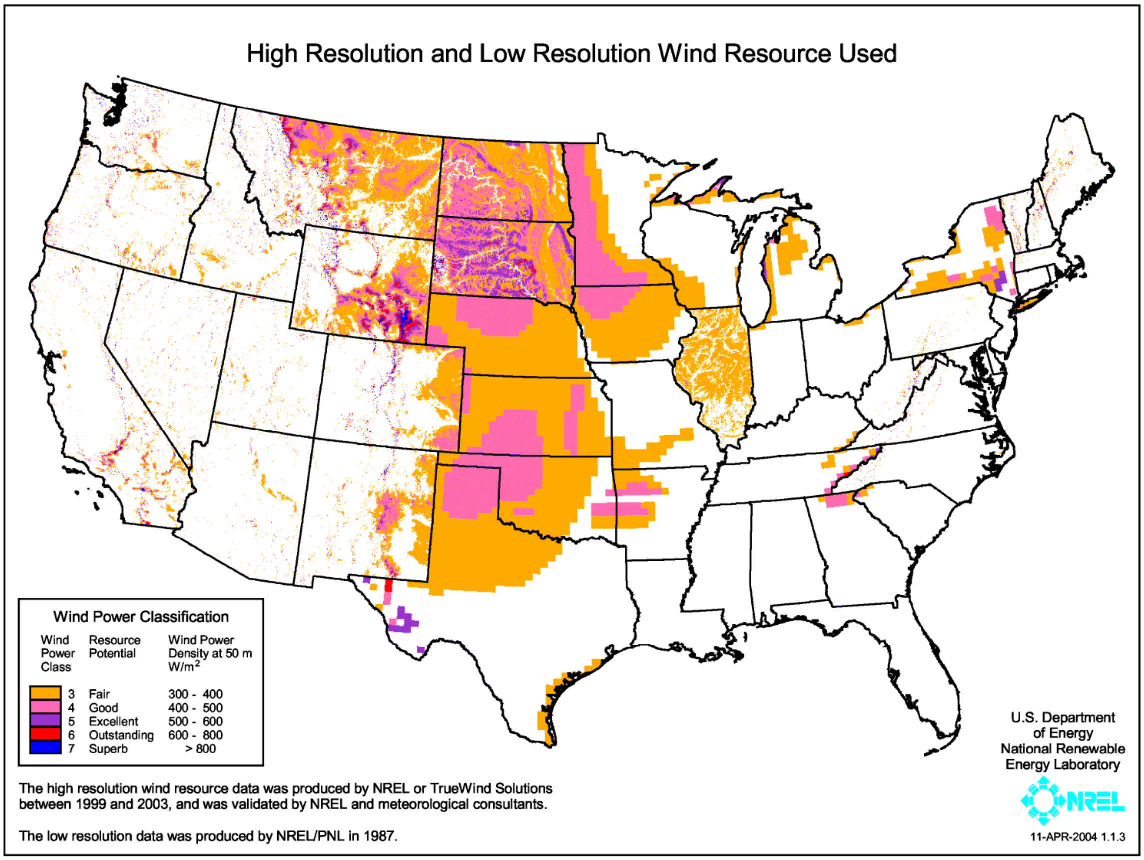

FIGURE D-1 Wind Resource Distribution Map for the 48 Contiguous United States (Source: EERE 2004b)

The developer must understand the time variability of the instantaneous wind speed. The ideal wind regime is one at which the instantaneous wind speed is near the upper limit of the operating range of commercially available wind turbines for the greatest percentage of time over the course of the year, thus maximizing annual energy production. (See Section D.5.3 for additional discussion on turbine operating ranges.) Therefore, the first step in any future wind farm development involves the collection of meteorological data (primarily wind speed and direction) at a potential candidate site for at least 1 year. For candidate sites in complex terrain or in areas with weather extremes, as many as 3 years of meteorological data may be necessary to support site development decisions. To realize their fullest value, the data must be collected at various locations within the site to support "micrositing" decisions (e.g., selecting the precise positioning of a wind turbine) and at various elevations to validate wind turbine decisions (e.g., selecting a turbine model and tower in which the rotor hub can be positioned at or near the elevation of maximum wind speed within its operating range and at a sufficiently high elevation so as to be above the chaotic and potentially damaging wind turbulence at or near the ground surface).[2] When the wind regime is precisely mapped, wind farms can consist of a variety of turbine models operating at different hub elevations to reach maximum sitewide efficiency. However, this type of composition complicates site development, construction, operation, and maintenance and may also complicate the collection and conditioning of the electric power that is generated. The use of various turbine models is unlikely; however, placing turbines at different hub elevations is technically feasible.

D.3.2 Other Factors in Site Selection

Site selection primarily involves matching wind regimes to turbine performance characteristics. The wind's elevation profiles and variability over time and location, as well as the range of extant wind speeds, must be matched to turbine designs (and vice versa). All such efforts to find the perfect match are conducted with the intention of maximizing the capacity factor of each turbine. This capacity factor is the ratio of expected energy output to the turbine's maximum rated power capacity, expressed as an annualized percentage (see additional discussion on capacity factors in Section D.5.3). A wind farm's expected capacity factor is the single greatest influence on the farm's return on investment (ROI).

Obviously, selecting a location with the highest average wind speed within the operating range of the proposed wind turbine for the greatest percentage of time is a principal site selection objective. In practice, many other circumstantial factors, such as transmission access and road access, substantially affect the costs of site development and O&M; therefore, they also play a key role in site selection.

D.4 WIND TURBINE TECHNOLOGIES

The centuries-old history of efforts to harvest wind energy is fascinating, and an extensive discussion is beyond the scope of this PEIS. However, many excellent sources exist, including Gipe (1995), Hau (2000), Burton et al. (2001), Manwell et al. (2002), and Wilson (1994) and the references therein, as well as Web sites maintained by the DOE Office of Energy Efficiency and Renewable Energy (EERE 2004a), NREL (2004a), Sandia National Laboratories (2004a), the National Wind Coordinating Committee (NWCC 2004), and the American Wind Energy Association (AWEA 2004c).

Sailing ships probably represent the earliest attempt to harness the wind. Windmills, the most familiar wind technology, have been used for myriad applications, most commonly to grind grain and pump water and crude oil. There is speculation that the earliest windmills went into service more than 3,000 years ago. More reliable historical documentation dates the earliest use of windmills to 200 B.C. in Persia (now Iraq) (Sandia National Laboratories 2004a). There is

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[2] Although actual measurements of wind profiles at candidate sites are preferred, statistical methods can be utilized to extrapolate wind data from one site to nearby sites. An exhaustive discussion of these statistical methods is beyond the scope of this PEIS; additional information can be obtained from appropriate engineering texts (e.g., Burton et al. 2001; Manwell et al. 2002).

also evidence that windmills may have been used much earlier in China to drain rice fields, but the earliest dates of service are unclear. The use of windmills to generate electricity began in the late 19th century to provide electric power in rural areas, before the advent of far-ranging power transmission and distribution systems. Many windmills used in rural areas of Europe and the United States to pump water were converted for the production of electricity. Windmills such as the one shown in Figure D-2 were used to generate small amounts of electricity, normally to satisfy the demand for electric power in the immediate vicinity.

FIGURE D-2 Great Plains Windmill (Source: EERE 2004a)

Windmills are the progenitors of the modern wind turbine.[3] In fact, they share a common fundamental function: converting the kinetic energy of the wind into the mechanical energy of a rotating shaft. Throughout the development and evolution of the windmill, a variety of designs have been explored. The evolution of wind turbine design has followed a similar path. The earliest windmills had their axis of rotation oriented vertically, and vertical-axis wind turbines (VAWTs) were also developed. Later-model windmills have their axis of rotation in the horizontal position, and the analogous horizontal-axis wind turbines (HAWTs) also evolved. Although the orientation of the rotational axis defines the two primary design categories of wind turbines, many variations exist within each category.

Early sailing ships and the earliest windmills utilized the principle of “aerodynamic drag” to capture wind energy. Applying this principle involves installing an obstruction in the path of the wind. Depending on how this obstruction is oriented and what it is connected to, the force of the wind striking it can cause work to be performed (e.g., propelling a square-rigged sailing ship through the water). The common instrument for measuring wind speed, the cup anemometer, is an example of a present technology that still utilizes aerodynamic drag. Machines utilizing aerodynamic drag are easy to construct, and they make few design or operational demands. However, despite the relative simplicity of aerodynamic drag machines, their overall efficiency is generally low.

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3 For this discussion, a wind turbine is defined as any device operated expressly for generating electricity, regardless of whether that electricity is utilized locally or introduced into power transmission and/or distribution systems.

No modern wind turbine operates on the principle of aerodynamic drag; instead, "aerodynamic lift" is utilized. When this principle is employed, the wind turbine's blades do not obstruct the wind; rather, they direct its flow. The cross-sectional shape of all modern wind turbine blades is that of an "airfoil." These blades are similar in shape and purpose to an airplane wing. Wind flowing around an airfoil creates two different regions of pressure: a low-pressure region on the convex or "suction" side of the airfoil, and a higher-pressure region on its concave or "pressure" side. The atmosphere's attempt to return to pressure equilibrium creates the phenomenon of aerodynamic lift. However, whereas an airplane's airfoils are oriented in such a way that aerodynamic lift helps the plane defy the laws of gravity (i.e., air pressure is lower above the wing than below it, causing the wing to "lift"), the orientation of a wind turbine's blades relative to incident wind converts aerodynamic lifting forces into the rotation of the blades around an axis parallel to the direction of the wind.[4] Wind turbines utilizing aerodynamic lift can have power efficiencies up to 50 times greater than the efficiencies of turbines operating on aerodynamic drag (Wilson 1994).

As noted previously, wind turbines have been developed with their axis of rotation in both the vertical orientation and the horizontal orientation. The VAWT traces its ancestry farther back in time than does the HAWT, to as early as 200 B.C. (Sandia National Laboratories 2004b). Modern VAWTs are variations of a design first introduced by French scientist Georges Darrieus around 1920. Figure D-3 shows examples of a commercial VAWT in California and an experimental VAWT currently operating at a DOE test facility in Texas.

In theory, both VAWTs and HAWTs should be able to capture the wind's energy by means of the principle of aerodynamic lift. However, VAWTs have a number of practical advantages. Because their blades are always perpendicular to the prevailing wind, they do not need to be reorientated when the wind direction changes in order to operate at their maximum efficiency. Thus, both their design and the complexity of their required operational controls are simplified. They are generally easier to erect than HAWTs and can have serviceable components located at or near ground level, thereby greatly simplifying their O&M. However, some of those same design characteristics contribute to the VAWT's intrinsic limitations. Many VAWT designs are not "free-wheeling" and must use an external energy source to start their rotation. Many also have limited wind speed operating ranges. VAWTs also have certain design limitations with respect to their maximum practical height.

Most important to their commercial application, however, is blade reliability and working life. VAWT blades must pass through the "wind shadow" or wake of their rotational axis, which also serves as the machine's primary support. This region typically exhibits a good deal of turbulence, which not only reduces power capture efficiencies but also subjects the blades to forces that are different and opposite to those that they experience when they are upwind of the center support; thus, significant engineering issues, such as fatigue, are introduced. Considerable research continues even today on how to overcome the intrinsic shortcomings of VAWTs, and VAWTs are being used as test platforms to generally advance the understanding of wind turbine

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4 Empirical studies have shown that the greatest turbine efficiencies are realized when the turbine rotor's axis of rotation is tilted slightly from the horizontal.

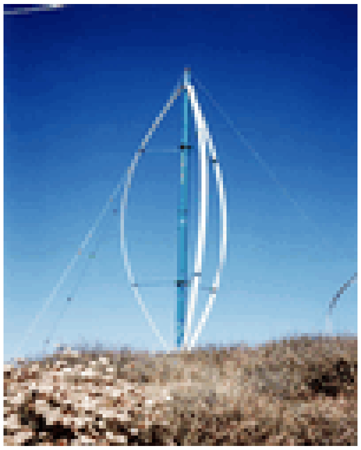


FIGURE D-3 Examples of VAWTs (Left: FloWind Corporation VAWT at Tehachapi, California. Photo credit: R. Thresher. Source: Photo #04688, NREL 2004b. Right: Darrieus-design VAWT operated as a wind energy technology test bed by Sandia National Laboratories at the U.S. Department of Agriculture research station at Bushland, Texas; 138 ft (42 m) high, 112 ft (34 m) in diameter. Photo credit: Sandia National Laboratories. Source: Photo #01671, NREL 2004b.)

technology. DOE's Sandia National Laboratories play a key role in this effort. However, only a few commercial wind farms that utilize VAWTs have ever been developed, and none are anticipated in the foreseeable future. Wind farms at Tehachapi Pass in California; Pincher Creek in Alberta, Canada; and Cap-Chat in Quebec, Canada, utilize or have utilized VAWTs. The leading manufacturer of commercial VAWTs, FloWind Corporation, is no longer in business. No VAWTs have ever gone into commercial service in Europe (Gipe 1995). Therefore, it is likely that HAWTs will continue to dominate the commercial market in the foreseeable future. Additional discussion of VAWT technology is therefore unnecessary for purposes of this PEIS.

In recent years, HAWTs have become the predominant technology used in commercial wind farms; thus, they are the focus of discussion in this PEIS. Figure D-4 shows an example of a typical front-facing HAWT. Within this category, Manwell et al. (2002) identified the following significant design variants: front-facing or rear-facing rotors and blades, rigid or teetering hubs, rotor rotation controlled by pitch or stall, number of blades (usually two or three), and free or controlled yaw motion. The majority of these design characteristics influence the overall performance of a turbine, but most have little or no influence on the environmental impacts of an operating turbine and thus are not discussed in further detail.

FIGURE D-4 Typical Front-Facing or Upwind HAWT (GE's 3.6-MW prototype wind turbine is an example of a front-facing HAWT. It is one of the largest HAWTs in existence, with a rotor diameter of 341 ft [104 m], giving a swept area of the blades of 91,432 ft^2 [8,495 m^2]. Rotor speed is variable between 8.5 and 15.3 rpm. The tower is constructed of concrete [lower portion] and tubular steel. Here, the turbine faces into the wind, which enters from the left. Sources: Photo adapted from EERE 2004c. Turbine specifications available from GE 2004.)

D.5 IMPORTANT CONCEPTS OF MODERN HAWT OPERATION

Figure D-5 shows the major components of a HAWT. As noted previously, many factors influence the design and performance of modern wind turbines. This section focuses on the aspects of wind turbine design and operation that can have direct and/or cumulative environmental impacts. Also discussed here is the spatial arrangement of wind turbines on a wind farm, which can also result in environmental impacts.

D.5.1 Power Coefficients

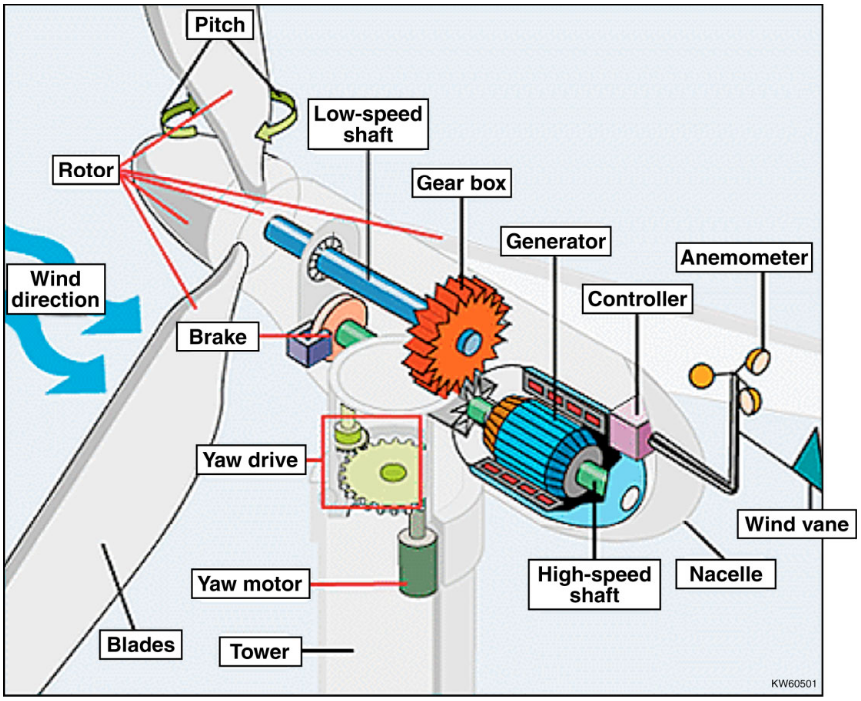
Intercepting the greatest practical cross-sectional area of wind creates the opportunity for capturing the greatest amount of energy; therefore, the primary design focus is on the rotor, which is the part of the turbine that actually extracts the wind's energy. No mechanical device, including the wind turbine, is 100% efficient. The practical efficiency of a wind turbine is usually represented as its power coefficient, C_p, defined as that fraction of the wind power that may be captured by the turbine and converted to mechanical work (and, subsequently, electricity). The power coefficient of a wind turbine is almost entirely a function of the rotor's efficiency. The power coefficient is represented by the following expression:

$$P = ½ \times C_p \times \rho \times A \times V^3, \quad \text{(D.3)}$$

where

P = power output of the turbine,

C_p = power coefficient of the rotor,



Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to “lift” and rotate. Front-facing turbines normally have three blades.

Brake: A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Controller: The controller starts the machine at wind speeds of about 8 to 16 mph (13 to 26 km/h) and shuts off the machine at about 65 mph (105 km/h). Turbines cannot operate at wind speeds above about 65 mph (105 km/h) because their generators could overheat.

Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1,200 to 1,500 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine, so engineers are exploring “direct-drive” generators that operate at lower rotational speeds and do not need gear boxes.

Generator: Usually an off-the-shelf induction generator that produces 60-cycle alternating current (ac) electricity.

High-speed shaft: Drives the generator.

Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rpm.

Nacelle: The rotor attaches to the nacelle, which sits atop the tower and includes the gear box, low-speed and high-speed shafts, generator, controller, and brake. A cover protects the components inside the nacelle. Some nacelles are large enough for a technician to stand inside while working.

Pitch: Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor: The blades and the hub together are called the rotor.

Tower: Towers are made from tubular steel (shown here) or steel lattice. Some taller towers may incorporate concrete over the lower portions of their height. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

Wind direction: This is an “upwind” turbine, so-called because it operates facing into the wind. Other turbines are designed to run “downwind,” facing away from the wind.

Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines do not require a yaw drive, since the wind blows the rotor downwind.

Yaw motor: Powers the yaw drive.

FIGURE D-5 Major Components of a Modern HAWT (Source: EERE 2004c)

ρ = air density (typically 2.70 lb/m^3 [1.225 kg/m^3] at sea level and 59°F [15°C]),

A = rotor-swept area, and

V^3 = cube of the incident wind speed.

The power coefficient of the rotor has a theoretical maximum value of 0.593, called the Betz limit or Lancaster-Betz limit. This value is based upon the physical reality that even the most aerodynamically efficient turbine blade disrupts the airflow of incident wind, even before the wind front reaches the rotating blade. In actuality, the air molecules within the cross-sectional area swept by the rotor slow down as they approach rotating turbine blades and thus lose kinetic energy proportional to the cube of that velocity loss.[5]

The power coefficient of the rotor can be thought of as a correction factor, introduced into the above power equation to reflect the reality that the rotor's power-capturing efficiency is less than perfect. To calculate the power coefficient of the entire wind turbine, one simply has to introduce additional correction factors to represent the mechanical inefficiencies of the entire turbine drivetrain. However, for the purpose of this discussion, the power coefficient of the rotor is the source of greatest turbine inefficiency to the extent that drivetrain inefficiencies need not be discussed in detail.

A comparison of the turbine efficiency equation above with the equation presented in Section D.3, which represents the power inherent in the wind, leads one to fully appreciate how energy is produced by wind turbines. The Betz limit actually reflects the impossibility of extracting all the energy from the wind. Because the theoretical limit of rotor efficiency is always considerably less than 100%, the power produced by a wind turbine is always less than the power contained in the wind cross section that the turbine is intercepting. And because the rotor's efficiency is the major contributor to the overall turbine efficiency, rotor design considerations are of paramount importance.

D.5.2 Turbine Power Curves

The graphical representation of a turbine's electric power output as a function of incident wind speed is known as the turbine's power curve. At a fixed rotor speed, the power production of a wind turbine is defined by the following equation:

$$P_{el} = c_p \times \rho/2 \times (v_w)^3 \times A \,, \qquad \text{(D.4)}$$

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5 The Betz limit is named after Albert Betz, the German dynamicist who first identified and defined the phenomenon. A more detailed discussion of the influence of turbine blades on airflow and the derivation of the Betz limit is provided in Burton et al. (2001).

where

P_{el} = electric power (expressed in W, kW, or MW),

c_p = power coefficient of the turbine,

ρ = air density (kg/m^3),

v_w = wind speed (m/s), and

A = swept area of the rotor (m^2).

Turbine manufacturers routinely use the power curve as a representation of their wind turbine's official certificate of performance.

Certain design features can have minor influences on the exact shape of the power curve; however, these influences notwithstanding, the power curves of virtually all commercial wind turbines are strikingly similar. As incident wind speed increases from zero to the "cut-in velocity," the net power extracted from the wind becomes greater than that which is necessary to overcome the mechanical drag of the turbine's drivetrain, and the excess power is used to begin producing usable electric power. With increasing wind speed, power production increases rapidly until the "rated velocity" is reached. At this wind speed, the turbine has reached its maximum electric power production capability. Power production continues at this maximum level with further increases in wind speed until the "cut-out velocity" is reached. At the cut-out velocity, the wind's energy is so great that it can cause mechanical damage to major turbine components. To prevent such damage, designers introduce various controls (such as pitch and stall control on the rotor, mechanical braking of the rotor shaft, and clutching mechanisms on the rotor shaft) that can decouple the rotor from the remainder of the turbine drivetrain.[6] With the application of such controls, the electric power production drops precipitously to zero, and the turbine effectively becomes nonfunctional as a power source. The range of wind velocities over which the turbine can produce electricity is referred to as its operating range; however, the maximum electric power production (i.e., the turbine's nameplate rating) is achieved only at the upper end of the operating range. At incident wind speeds between the cut-in velocity and the rated velocity, power production is well below the nameplate rating. In general, commercial wind turbines have operating ranges between 2.5 and 25 m/s. (Table D-2 in Section D.6, which provides commercial wind industry profiles, has examples of operating ranges.)

A turbine's power output can be derived solely from engineering calculations. However, because the power curve represents the manufacturer's guarantee of a turbine's performance, theoretical calculations are also carefully validated with real-world measurements. To overcome myriad real-world variables that can affect power production, such empirical verifications of power output are based on the statistical evaluation of a large number of measurements.

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6 In practice, such controls can be applied at any point throughout the operating range of the turbine to maintain the quality of electric power being produced and to overcome the real-world variability in incident wind energy over time.

Hau indicates that measurements averaged over a minimum of 10 minutes are usually sufficient to account for the time variability of operating conditions (Hau 2000).

D.5.3 Capacity Factors

Although the power curve is an accurate measure of the turbine's ability to generate electricity from incident wind, it does not adequately describe expectations of real-world power production. Overlaying the relevant characteristics of a given wind regime (most importantly, the percentage of time the incident wind is at the uppermost portion of the operating range) and introducing additional correction factors that reflect the turbine's technical availability (i.e., periods when the turbine is fully functional and not down for maintenance or repairs)[7] yield the capacity factor, the most realistic and reliable prediction of the energy yield for a given candidate site. Capacity factors are dimensionless, expressed as a ratio in which the turbine's annual predicted energy production is divided by the energy it would produce if it operated at its nameplate rating continuously. Capacity factors are normally represented as annualized values to account for seasonal variations in wind regimes. In practice, the most efficient wind farms exhibit individual turbine capacity factors of 30 to 35% (EPRI 2001; DOE/TVA/EPRI 2003; Robichaud 2004). However, capacity factors as high as 45% have been observed (Manwell et al. 2002; EPRI 2001; McGowan and Conners 2000). Capacity factors of at least 25% are considered minimally necessary for a site to be considered economically viable (McGowan and Conners 2000).

Because it is rooted in the real world, the capacity factor becomes a much more valuable tool for supporting decisions about wind farm development than the turbine's power curve alone. The ideal site from a power production perspective is one that yields the highest capacity factor for each of the turbines. That being said, however, it is important to also recognize that power-producing potential, although important, is not the exclusive basis for site development decisions. Many other factors, including ease of site access, access to transmission lines, site development costs, the absence of sensitive ecosystems, and market price for energy, are always also considered in site selection decisions. Thus, it is often the case that the sites with the ideal wind regimes yielding the highest predicted capacity factors are not necessarily assigned the highest priority for development.

D.5.4 Rotor Tip Speed and Tip Speed Ratio

The rotor tip speed is the tangential velocity of the very end of the blade of a rotating rotor (i.e., the speed at which the tip of the blade moves around the circumference of the swept area of the rotor). Early wind turbine designs sought to match the rotor speed with the rotational speed requirements of the electric generator's rotor.[8] However, modern designs utilizing more

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[7] Hau (2000) cites studies from Denmark and Germany that support the claim that annualized availabilities of modern-day wind turbines can approach 98%.

[8] The center shaft, or rotor, of a typical induction generator rotates at 1,500 to 2,000 rotations per minute (rpm).

sophisticated and more reliable transmissions (Figure D-5) can adequately maintain the rotational speed of the electric generator's central shaft at much lower rates of rotor rotation. This results in substantial additional benefits, including reductions in the bending moments on the blades and reductions in the forces on the turbine drivetrain, by minimizing the effective weight of the rotor.

Wind turbine designers concern themselves not with the blade's tip speed but rather with the tip speed ratio, which is defined as the ratio of the angular velocity of the blade tip to the mean velocity of the wind entering the rotor. For a given mean wind velocity and a rotor with a given number of blades, the design objective is to select a tip speed ratio that maximizes the opportunity for the incident wind to interact with the turbine blades and impart aerodynamic lift while simultaneously minimizing the disruptions of airflow ahead of the rotor blades. A rotor spinning too fast will present a greater obstruction to incident wind. Conversely, a rotor revolution that is too slow will allow large amounts of air to pass through the rotor's plane without ever interacting with a turbine blade and imparting aerodynamic lift. At a given mean wind speed, the power coefficient of a turbine initially increases with an increasing tip speed ratio until a maximum is reached; beyond this point, performance actually decreases with further increases in the tip speed ratio. A more detailed discussion of this relationship and the influence of the Betz limit on turbine performance is provided by Burton et al. (2001). The ideal tip speed ratio is empirically derived and is inversely related to the number of blades. Because the rotor's (and the turbine's) power coefficient is directly related to the tip speed, controlling that ratio is a desirable objective. For a specific rotor operating in a given wind regime, the tip speed ratio at which maximum performance is achieved becomes the controlling design basis value.

In addition to the basic performance relationship between the blade's tip speed and the turbine's power coefficient, two impacting factors are directly related to rotor rotation and tip speed: aerodynamic noise and shadow flicker. Both can influence turbine design decisions. The aerodynamic noise generated by a wind turbine is proportional to the fifth power of the tip speed.[9] Thus, small variations in tip speed can dramatically affect the noise profile of a wind turbine. Empirical data have led turbine designers to limit the tip speed to no more than 213 ft/s (65 m/s). Limiting the tip speed (which is proportional to the rotor's rate of rotation and based on the swept area of the rotor) and limiting the distance to the nearest habitation to at least 1,312 ft (400 m) are expected to result in a turbine noise level at or near ambient levels (Burton et al. 2001). However, other factors, such as the height of the rotor and the topography of the site, can significantly influence the propagation of sound energy.

In addition to the mathematical and geometric relationships between the rotor's rate of revolution and the tip speed and the relationships between the tip speed ratio and the power coefficients, rotor revolution can also cause a visual phenomenon unique to wind turbines known as shadow flicker. Shadow flicker refers to the shadows that a wind turbine casts over structures and observers at times of the day when the sun is directly behind the turbine rotor from an observer's position. Shadow flicker is most pronounced in northern latitudes during winter months because of the lower angle of the sun in the winter sky. However, it is possible to

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[9] The angle at which the airfoil of a rotor blade faces the wind, sometimes known as the angle of attack, can also influence the production of aerodynamic noise.

encounter shadow flicker anywhere for brief periods after sunset and before sunrise. Empirical data suggest that shadow flicker can have a disorienting effect on a small segment of the general population. Empirical data also suggest that limiting the frequency of rotor rotation to below 2.5 Hz can mitigate the deleterious effects of shadow flicker.[10] Burton et al. (2001) indicates that limiting a (three-bladed) rotor revolution to 35 rpm will result in a blade passing frequency of 1.75 Hz (i.e., where the passing is between the sun and the observer). Increasing the spacing between a turbine rotor and the nearest observer to at least 10 rotor diameters also dramatically mitigates shadow flicker effects.

Finally, another closely related phenomenon is "blade glint," which is the reflection of sunlight off the surfaces of rotating blades. Such glint can also have a disruptive effect on some observers. However, as discussed elsewhere, the trend in the industry is toward longer blades. To control the resulting weight (and provide better aerodynamic properties), modern blades are now constructed almost exclusively of carbon composites or plastics, the natural surfaces of which are quite dull, especially relative to the steel and aluminum blades of the past. In the majority of cases, this technological development has made blade glint a relatively moot point with regard to modern turbines.

D.5.5 Blade Length and Tower Height

Because the speed of the incoming wind cannot be controlled, attaining and maintaining the ideal tip speed ratio involves controlling the tip speed. There are two paths to this objective: changing the rate of rotor rotation or increasing the blade length. Increasing the blade length is often the preferred option for a number of engineering reasons. However, the law of diminishing returns is also at play here. Larger rotor diameters result in additional bending moments on the blades that must be accounted for. Longer blades mean additional rotor weight and increased strain on the mechanical drivetrain components. Research on alternative materials and fabrication procedures is being conducted by turbine manufacturers and under government sponsorship. (See Section D.7 for more details on blade research.) Preliminary DOE-sponsored research on the technological impediments to scaling up current blade designs has identified the need to modify construction materials and processes (Griffin 2002) and the need to take a fundamentally different approach to airfoil design for extremely long blades (TPI Composites, Inc. 2002).

To accommodate longer blade lengths, the turbine support towers have to be taller and more substantial. Irrespective of blade length, taller towers allow the rotor to operate in geostrophic wind regimes above the interferences introduced by surface topography. Principal performance factors affecting tower height selection include the wind profiles of the candidate site and the blade length of the turbine model selected. Costs of fabrication and erection are balanced against the performance advantages. Other factors related to site conditions can also influence tower height selection. These include access to the site by the larger equipment needed to transport towers (or tower segments), longer blades, and lifting/erection equipment; temporary

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[10] One hertz, or one cycle per second, is equal to 1/60th rpm.

amendment of site surface conditions to accommodate erection activities; and subsurface conditions that could affect the difficulty and the cost of constructing sufficient foundations for larger towers.[11] Installation costs, site access, and transportation logistics are important limiting factors with regard to tower height, and all factors must be considered in calculating improved performance with height. Developers are not likely to erect towers any taller than necessary to achieve economic power production (Steinhower 2004).

The principal impacting factors that directly relate to a rotor's geometry and the elevation at which it operates are listed below:

- Larger rotors require higher, more formidable towers that are more expensive to fabricate and erect.

- Higher towers, in turn, are visible from greater distances, increasing the size of the impacted viewshed.

- Larger rotors allow for the economical capture of wind energy at slower rotor revolutions, which could lessen or completely eliminate the adverse viewshed impacts and bird-strike hazards.

- Larger rotors can rotate at frequencies less than the frequencies that induce shadow flicker.

- Larger rotors operating at fewer rotations per minute produce less aerodynamic noise than their smaller counterparts, which must rotate faster to capture the same amount of wind energy.

D.5.6 Grid Interconnection Issues

The distance to an existing transmission line of suitable voltage and with reserve power-carrying capacity is a critical factor to consider with regard to future wind energy development projects, because the wind farm developer is expected to absorb the cost of establishing the physical link from the wind farm to the nearest existing transmission grid.[12] However, connecting to the grid is not necessarily a straightforward process. In reality, many factors related to grid interconnectivity can influence site development costs, design selection, initial installation and subsequent operating costs, and ROI schedules.

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[11] However, innovative tower designs can dramatically influence erection costs and simplify transportation logistics. See Section D.7.1 for additional discussion.

[12] Detailed discussions on the development of interconnecting links to existing transmission lines are provided in the cumulative impacts portion of this PEIS. Nevertheless, the development of power links between any wind farm and existing power transmission lines will receive separate National Environmental Policy Act (NEPA) evaluations, which are outside the scope of this PEIS.

To prevent disrupting the grid, the electric power generated at the wind farm must first be conditioned. This requires installing various power management and conditioning devices. Other devices are required to automatically isolate a wind farm from the grid during certain disruptive events. Sophisticated supervisory control and data acquisition (SCADA) systems are also required to ensure that the operating conditions of both the individual turbines and the overall wind farm and any rapid changes to grid interconnections are adequately controlled, in order to prevent the effects of potentially damaging disruptive events at the wind farm from cascading onto the grid.

Although power management and control devices and SCADA systems certainly affect site development costs and the ability of the wind farm to interconnect to the grid, they represent only an incremental change to the footprint of the wind farm, and most have little or no direct or cumulative environmental impacts.[13] There are two notable exceptions, however: "voltage flicker" and lightning protection.

If not adequately conditioned and controlled, wind farm power introduced onto the grid can result in voltage flicker. Voltage flicker occurs when changes to the network voltage occur faster than steady-state voltage changes that exist within the transmission system. Voltage flicker can cause perceptible changes to the brightness of incandescent lights that draw power from the grid. Such changes, in turn, can have a disorienting effect on certain individuals. Transmission grid operators can be expected to require wind farm operators to establish power management systems capable of eliminating conditions leading to voltage flicker.

Lightning protection is also required for wind farm components to prevent catastrophic impacts to the grid. Each individual turbine tower on the wind farm, as well as the electrical substation, must be protected, and control systems must be capable of isolating the wind farm from the grid during upset conditions caused by lightning. Although lightning protection technologies are available, their application in some wind farm settings may appreciably increase site development costs. Conventional lightning control involves providing a low-impedance path for the lightning's electrical energy to pass to the ground.[14] To establish adequate lightning protection for wind farms developed on rocky ground where there is no soil mantle, it may be necessary to drill one or more wells into which a current-conducting metal rod is inserted to extend the grounding path to the nearest aquifer. Moreover, the aquifer must be continuous over a large area rather than perched to provide reliable protection. In some western states within the study area, the nearest appropriate aquifer may be thousands of feet below a candidate wind site. Installation of such grounding wells will increase costs — not only costs directly related to well

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[13] Although many issues associated with power management and control and interconnection to the grid are outside the scope of this PEIS, they are, nevertheless, expected to be stipulations to any agreement between a power transmission company and a wind farm operator regulating grid interconnection.

[14] Where the soil mantle provides adequate grounding capacity, lightning protection systems routinely involve one or more grounding rods. For electrical substations, this grounding path is often enhanced by the installation of a grounding grid of wire located below the entire footprint of the substation and at some depth below the ground surface.

installation, but also costs to support the hydrogeologic studies that may be required to identify appropriate aquifers.[15]

D.5.7 Variable versus Fixed Rotor Rotation

Wind turbines can be designed to operate at both fixed and variable rotor rotation speeds. Of the two systems, variable-speed systems are preferred for a number of reasons related to overall wind turbine performance. However, while variable-speed machines can take fuller advantage of variations in the incident wind speed, the alternating current (ac) electricity they produce has a variable frequency that cannot be safely delivered to existing power transmission grids without conditioning. Variable-speed wind turbines are routinely connected "indirectly" to the grid to allow this power conditioning to occur at the wind farm. The majority of modern turbines include transmissions, clutches, and rotor shaft braking systems or aerodynamic stall features that act on the rotor blades to maintain the variations in a rotor shaft's rotation within prescribed design limits. Such turbines are also equipped with SCADA systems that can adjust operating conditions (e.g., aerodynamic stall and blade pitch) to changing wind conditions. Variable-speed capability allows the turbine to operate at ideal tip speed ratios over a larger range of wind speeds. The most dramatic increase in performance is realized at lower wind speeds.

Wind turbines with either a fixed or variable rotor rotation speed can be outfitted with either synchronous or asynchronous electric power generators.[16] In general, initial installation costs for asynchronous generators are lower, and the generators are generally very reliable. More important, asynchronous generators have mechanical properties that make them very suitable for wind turbine applications, including good overload capabilities and a relatively small generator slip.[17] Asynchronous generators can easily accommodate changes in the torque applied by the wind turbine's rotor shaft (through the transmission), thus reducing overall mechanical wear and tear over the generator's operating life. Because of the relatively constant operating conditions of asynchronous generators, turbines equipped with such generators are normally directly connected to the grid with little additional conditioning.

The use of synchronous electric generators rather than induction generators improves the wind turbine's overall power-generating performance and reduces the likelihood that the turbine will be a source of harmonic electric currents that can be disruptive to the power grid. However,

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[15] Properly designed and installed "grounding wells" have no potential to adversely impact groundwater quality.

[16] Asynchronous generators are also commonly called induction generators. Expanded discussions on electric generators are available in appropriate engineering textbooks. A simplified discussion regarding generators used in wind turbines can be found in DWIA (2004).

[17] The difference in rotational speeds of the generator at idle and at peak load is called the generator slip, expressed as a percentage of the synchronous speed. Thus, the rotational speed of the generator's center shaft (called the stator), which is turned by the action of the turbine rotor, varies little over the entire operating range of the generator.

initial installation costs are higher, and the power produced by synchronous generators must first be conditioned before delivery to the grid, further increasing installation and operational costs.

As rotor diameters increase, the turbine's rated power increases proportionally to the square of the rotor diameter. The amount of torque produced by the rotor shaft also increases markedly, placing significant operating demands on transmissions and generators. Industry and government researchers are now exploring the use of multiple generators or the use of multipole generators as a way of distributing torque and reducing its damaging effects on mechanical systems (Cotrell 2002). The use of multiple generators operating at different shaft speeds is also being investigated as a means of producing optimal levels of power at more widely varying rotor rotational speeds. Regardless of turbine and generator design choices, the attendant power-conditioning prerequisites do not themselves have additional environmental impacts of any significance.

Operation at variable rotor speeds increases the complexity of the initial turbine design as well as the SCADA system required. However, it also promises to increase the overall longevity of major system components and to reduce O&M costs. Thus, turbines with variable-speed rotors can be expected to have less of an environmental impact over their operating lives than would their fixed-speed counterparts.

Wind farms could consist of a mixture of fixed-speed and variable-speed turbines. Although the development costs of such a wind farm would be incremental, the increased sophistication of power management systems and SCADA systems and the expected greater O&M costs of such a configuration make such a wind farm unlikely. Wind farms consisting of identical turbines operating at different rotor elevations in order to take the fullest advantage of existing wind profiles are still a conceivable option, however.

The following impacting factors relate to rotor operation at a variable rotation speed:

- Reducing the dynamic forces on the turbine drivetrain, extending the operating lives of major components, extending the maintenance intervals, and reducing the incidence of breakdowns, all of which would result in a smaller environmental impact over the life of the wind farm;

- Allowing the turbine to be "elastic" with respect to its interaction with the grid, thereby reducing the generation of power harmonics that can be disruptive to the grid; and

- Allowing the turbine to efficiently generate power at lower wind speeds, thus reducing the aerodynamic noise signal of the blades.

D.5.8 Micrositing and Site Development

Once a candidate site has been selected and more detailed meteorological data have been gathered for a minimum of 1 year, site developers have the data necessary to make micrositing decisions (i.e., determine the precise location on the site at which the wind turbines will be located). The natural turbulence at the site due to the surface topography and obstructions and the induced turbulence of each wind turbine tower are the primary factors that govern turbine micrositing. Empirically derived nomographs[18] exist that indicate the necessary minimum distances for turbine placement from natural obstructions; however, they are often imprecise. Improving the methods for characterizing site-specific turbulence and understanding the influence of turbulence on site development make up a major ongoing R&D initiative (Section D.7). It is possible that site developers may find it appropriate to remove some natural obstructions (e.g., trees) to mitigate turbulence caused by natural obstructions.[19] It is also reasonable to conclude, however, that the extent to which natural features of the site will be altered to improve the wind regime will be limited by site development costs. Thus, while tree removal is a feasible step associated with site development, major alterations of the existing grade over a large scale are not.

It is also reasonable to expect that a site developer will seek to take advantage of economies of scale and develop a candidate site to its fullest potential. Thus, multiple turbines will likely be erected, and turbulence considerations will again be the primary factor governing their number and interspatial relationships.[20] Empirical nomographs that describe the induced turbulence of a wind turbine and its tower and that indicate the minimum distance of separation needed to avoid such interferences will likely be used to support micrositing decisions. (Research is ongoing to develop more precise modeling tools for characterizing the wind regimes on a site; see Section D.7.) Avoiding the wind shadow of turbines will probably be a first priority in siting multiple turbines, and access to the indicated micrositing location will be of secondary importance. Pursuing economies of scale in site development will amortize site characterization and site development costs. However, the extent to which a site will be developed can have additive effects on many of its impacting factors.

Primary impacting factors related to site development and micrositing include the following:

- Potential for ancillary activities, such as tree and vegetation removal, that will result in surface scarring and additional impacts to the viewshed beyond the impact of turbine visibility itself;

[18] A nomograph is any chart representing numerical relationships. In this case, the relationship is between the degree of turbulence and the distance from a wind turbine to any natural or human-made wind obstruction, including other turbines.

[19] However, for wind turbines operating on very tall towers with their rotors largely within the geostropic wind regime, even mature trees represent relatively inconsequential ground-level obstructions to winds at the turbine hub’s elevation.

[20] The rotation of both a turbine rotor and the support tower induce turbulence in the downwind direction. Spacing of wind turbines to avoid turbulence effects is usually represented by rotor diameters. Normally, a distance of 10 rotor diameters is considered to be the minimum downwind distance for spacing turbines in the downwind direction.

- Increased potential for fugitive dust, proportional to the area of disturbed ground surface;

- Potential for invasive species being established in disturbed areas before indigenous vegetation can be reestablished;

- Potential for bird strikes, generally proportional to the number of turbines installed;

- Increased time required for construction, with proportional increases in both the magnitude and duration of impacts related to construction;

- Potentially additive impacts from individual turbines, including noise and viewshed impacts; and

- Proportional increases in O&M costs, including costs to deal with wastes associated with system maintenance and repair.

D.6 COMMERCIAL WIND ENERGY INDUSTRY PROFILES

This section provides an overview of the existing commercial wind energy industry within the study area. The AWEA compiles and maintains data on commercial wind farms.[21] The review and analysis of these data provide a reasonable basis from which to anticipate the characteristics of future wind farms.

Industrywide reviews of the commercial utility-scale wind energy industry have identified the following important trends, each of which will greatly influence future wind farms.

- In general, average individual wind turbine power-generating capacities have steadily increased in North America, from 500–750 kW in the late 1990s to megawatt-capacity turbine installations beginning in 1999, resulting in typical wind farm generating capacities of 50 MW or larger (Kaygusuz 2004).

- The (worldwide) average growth rate of the cumulative installed wind energy power-generating capacity over the period 1998 to 2004 has been about 30% per year (Kaygusuz 2004).

- As the understanding of aerodynamics has been increasing and as designs have been defined, wind turbine efficiencies have been increasing, especially for turbines with larger rotor-swept areas. Average annual yields per unit of rotor-swept area (RSA) have increased by more than 50% as rotor diameters have increased from 66 to 262 ft (20 to 80 m) (Milborrow 2002).

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21 The text box on the next page describes the AWEA and information compiled by the AWEA regarding the wind energy industry.